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Division of California Research & Technology, Inc., a ● TITAN company

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Final Letter Report

on

Concepts for Cavitation Alleviation
of
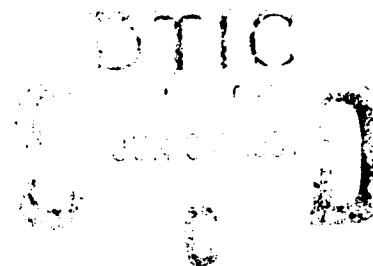## Banded and Ducted Rotor Tips

by

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under

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Executive Summary:

Problem: Explore concepts and recommend geometries for alleviating the cavitation sensitivity of blade-band junctions of banded and ducted underwater propellers.

Geometry: The baseline geometry is the tip region of a generic banded and ducted propeller design by Steve Neely of DTRC. Geometry was supplied by DTRC on February 5, 1991.

Approach: A lifting surface model of the tip region of the blade, the band and the duct wall was used to calculate in detail the blade load carry-over onto the band and the duct wall. Geometry modifications of the blade tip and the band camber were made to alleviate cavitation sensitivity. Two-dimensional models were used to assess the effect of blade and band thickness. Both design and analysis type codes were used.

Conclusion: With proper use of band camber, the suction pressure in the blade band junction can be tailored to alleviate cavitation.

Supporting
Documentation:

Detailed geometries and computed results were presented and delivered to DTRC personnel at an ARAP meeting on April 12, 1991.

Recommendations (Banded and ducted rotor tips):

1. The baseline geometry indicates a highly singular pressure loading on the band near the blade-band leading edge junction. A major design uncertainty is the blade angle of attack in the tip region. The ideal blade camber loading is always contaminated by some angle of attack component - certainly in off-design operation. A *flared-leading-edge-strake is recommended* to alleviate cavitation sensitivity due to this uncertainty. The amount of flare should be adjusted to the estimated uncertainty in the blade angle of attack. Guidelines for a flared strake design are included in the technical package.

2. To accommodate the blade leading-edge-strake, it is further *recommended that the band be moved forward* until the trailing edges of the blade and band are flush - about 14 percent of the blade tip chord. The strake can be designed by further raking the blade tip forward or holding the maximum thickness line constant. Some *forward-tip-rake is recommended* to reduce the strake length and so keep it as far as possible from the band leading edge.

3. Even omitting the blade loading, the band has a thickness-induced-interaction with the duct. The band is sucked towards the duct wall with an associated induced or interference drag penalty. It is *recommended* that a *uniform band camber* in the order of 1% chord be used to eliminate this load and unnecessary performance penalty. The band geometry and calculated load are included in the technical package.

4. This recommendation is concerned with the "proper" use of band camber near the junction to further reduce the peak suction pressure and tendency toward cavitation on the blade upper surface and neighboring band in the junction. It includes several parts:

- The blade load carry-over onto the band is asymmetric. That is, the suction load on the blade is felt as a suction load (away from the duct) on the adjacent part of the band and likewise the compression side of the blade is felt as a force directed toward the duct wall on the band. We *recommend a symmetric 3% band camber* at the ideal blade design angle of attack. Calculations indicate that the suction-side band loading can be virtually eliminated with an increase of the band load on the compression side. The band camber modification is confined to the vicinity of the junction (within a blade half chord). Also, it is of the opposite sign of the 1% uniform camber recommended above. This concept can be used to tailor the band suction pressure loading to alleviate cavitation. Examples are included in the technical package.

- An alternative approach for determining the band camber near the junction is the following. We first calculate the carry-over loading on the band close to the junction. Choose by good "engineering judgement" how many points of pressure coefficient you want to reduce the peak suction pressure. With the *assumed band-load increment* and a plausible assumption for the decay away from the junction, you then *calculate the induced band camber* - an inverse design procedure like the method used to generate

blade load distributions. This method was tried and it works quite well in producing the desired load distribution. Unfortunately, the induced band camber distributions do not seem practical (see example in the technical package). Perhaps with further refinement or by using constraints on the shape we could obtain better results. Our *recommendation at this point is to assume the camber distribution, calculate the load and iterate until you get the loading you want.* It takes a little practice but it works. The modified parabolic-camber-distribution in the technical package was developed with this approach.

● The *band-induced suction load due to blade thickness can also be removed* with the above method. This is a direct application of our dillet technology. An axial doublet model of the blade thickness and its image in the wall is used. The normal wash on the band is calculated and from that the induced camber. For the baseline thickness model this results in a *very shallow dillet* that is confined to the immediate neighborhood of the junction. The reason is that the wall constrains the induced velocity on the band. *This correction is not recommended for the current installation* but it should be kept in mind for future designs. The example is included in the technical package.

● *The bottom line is that with the proper use of band camber, it is possible to tailor the junction pressure loading to offset the sensitivity to cavitation on the blade and band suction surface.* It must be kept in mind that the recommended geometry change induces more positive loading on the opposite surface of the blade and band that could lead to separation. Also the suction pressure in the gap between the band and duct-wall could be driven below the cavitation threshold. Although our inviscid calculations do not indicate a problem on the wall, *viscous calculations in the gap are recommended* for determining the pressure levels a little more carefully.

5. In the early part of our program, we considered a geometry where the blade tip and band are raked aft such that all band overhang forward of the blade leading edge is eliminated. This is a complete departure from the idea of using the band as a splitter plate for the blade tip. The thinking is that the vorticity due to blade loading must eventually be turned downstream. Why turn it upstream on a forward raked tip or strake and then turn it downstream on the band? The modern winglet is designed to work on a swept back tip - the direction the vorticity wants to shed. Also the winglet has a high aspect ratio and the chord decreases towards the tip where the load falls off. The uniform-chord band configuration is much like the older idea of an end plate. The load is carried over but the penalty in increased profile and interference drag usually offsets any potential winglet advantage. *An alternate recommended design concept is to size the minimum band chord to meet the structural stiffness requirements and then contour the band chord and camber in the junction to realize the performance advantage!*

6. Finally we remark that serious thought has been given to the use of a *loop-blade concept* invented by Pien in 1976 for a free running propeller. For the ducted propulsor application, the bi-wing-blade or loop-blade has the potential for meeting the stiffness requirements while presenting minimal interference with the duct wall. Preliminary

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Trefftz plane calculations indicate a substantial performance enhancement due to the duct. We have submitted a proposal to ONR under the FY92 Applied Hydrodynamics Program for an in depth study and evaluation of this concept for ducted propeller applications. *We also recommend a follow on joint project with the DTRC Propulsion Branch to design a prototype of a ducted loop-blade configuration.*

Supplementary Documentation (contents):

1. Recommended Geometry and Options:

- Band camber to alleviate rotor tip cavitation sensitivity.
- Band camber induced by band thickness.
- Band camber induced by blade thickness (optional dillet).
- Flared blade strake design (guidelines with example).

2. Lifting surface calculations:
- Baseline configuration (DTRC design).
- Straked blade with cutaway.
- Cambered band configurations.
    - Parabolic.
    - Cosine.
    - Asymmetric cosine.
    - Cubic/Parabolic.
- Calculated band camber for assumed band load.
- Induced duct-wall pressure for selected cases.
- Example of aft raked band and blade tip.

Meeting at Titan/ARAP (April 12, 1991)

Detailed discussions of the calculated results and the recommended procedures and geometries took place on April 12, 1991 between Mr. Steve Neely and Dr. Ki-Han Kim of the DTRC Propulsion Branch and the authors of this report at Titan/ARAP. Two copies of the Supplementary Documentation were delivered to Mr. Neely and Dr. Kim. Questions concerning the content of this letter may be addressed to Dr. Yates or Dr. Parker at Titan/ARAP.